# On Adaptive Mesh Refinement in Wrinkling Prediction Analysis

A. Selman [1 *], T. Meinders [2], A.H. van den Boogaard [2] and J. Huetink [2]

[1]Netherlands Institute *for* Metals Research
Rotterdamseweg 137 – 2628 AL Delft
The Netherlands
*e-mail: a.selman@wb.utwente.nl*

[2] University of Twente
Department of Mechanical Engineering
P.O. Box 217
7500 AE Enschede – The Netherlands
*e-mail: v.t.meinders@wb.utwente.nl*
*a.h.vandenboogaard@wb.utwente.nl*
*j.huetink@wb.utwente.nl*

ABSTRACT: Hutchinson approach has been successfully used by a number of researchers in thin sheet metal forming processes for wrinkling prediction. However, Hutchinson approach is limited to regions of the sheet that are free of any contact. Therefore, a new wrinkling indicator that can be used in the contact areas is proposed. Discretisation error indicators are also used to present a comprehensive approach to wrinkling prediction analysis.

KEY WORDS: Numerical Simulation, Finite Elements, Sheet Metal Forming, Error Estimation, Wrinkling Prediction and Adaptive Mesh Refinement.

## 1. INTRODUCTION

In a numerical simulation, wrinkles can be detected by a visual inspection of the deformed mesh, provided that the finite element discretisation is fine enough to allow a proper capture of the wrinkles. This, in general, makes it cumbersome to proceed with the analysis. Rather, it is desirable to proceed with a selective refinement to keep the computational cost low (acceptable). This implies that some kind of wrinkling indicators are used to direct the refinement process [1-4].
In this context [5] and more generally in finite element simulations [6], adaptive mesh refinement plays an essential role.

In this work, the analysis of Hutchinson and Neale [7], which consists of formulating the problem within the context of plastic bifurcation theory for thin shell elements and its extension by Neale [8] to account for more general constitutive models, is used. Under a number of assumptions, limitations and simplifications a simple wrinkling criterion is obtained and used to locally define a wrinkling risk factor or simply a (contact free) wrinkling indicator which, in turn, is used to detect the zones (elements) to be refined in a subsequent adaptive mesh refinement process.

Hutchinson analysis is, unfortunately, limited to regions of the sheet that are free of any contact. When contact is taken into account the problem is further complicated. Furthermore, given that numerical simulations of complex sheet metal forming involve large scale models, it is obvious that global wrinkling indicators found in the literature - mostly based on eigen value analysis of the global tangent stiffness matrix - should not be used because of their high computational cost. Consequently, an indicator based on the local change of curvatures will be considered.

Finally, we note that in wrinkling prediction analyses, the local curvature, amongst other parameters such as the

[*] Please send all correspondence to: T. Meinders, University of Twente, Mechanical Engineering Department, Po Box 217, 7500 AE Enschede, The Netherlands.

thickness, plays a major role and should, therefore, be properly approximated from the finite element meshes at all stages of the computation. In this context, the incorporation of discretisation errors indicators and adaptive mesh refinement in sheet metal forming processes is doubly important in keeping the computation cost low and allowing a proper wrinkling prediction analysis.

## 2. DISCRETISATION ERRORS ESTIMATION

The error estimation used here is entirely geometrical and is based on the accuracy with which the finite element mesh can describe the continuous *exact* shape [5]. In addition to Bonet's geometric error estimation, a thickness error which measures the jump between the finite element solution and a solution obtained by some recovery technique to substitute for the exact solution, is also taken into account.

## 3. CONTACT FREE WRINKLING ANALYSIS

The basic theory of plastic buckling and relevant relations for the Donnell-Mushtari-Vlasov (DMV) shallow shell theory have been developed by Hutchinson [9]. The application of this theory to sheet wrinkling was first carried out by Hutchinson and Neale [7] and is used in the present work.

To determine the critical stress state for buckling that is needed in the definition of the wrinkling indicator, Hutchinson bifurcation functional [HUT 74] is used.

Using the critical stress values, a wrinkling risk factor (perpendicular to the first principal direction, for instance) can be defined as

$$f_\sigma = \frac{\sigma_1}{\sigma_1^{cr}} \qquad (1)$$

Therefore a wrinkling risk exists whenever $f_\sigma$ is larger than 1. This factor is used to select candidate elements for subsequent refinement.

## 4. WRINKLING WITH CONTACT

The present indicator is based on the change of curvatures (during a single deep drawing step) under compressive stresses. This filters out all changes in curvature that are not due to compressive stresses, such as those caused for example by the geometry of the tool and the die. Such changes are, nevertheless, taken into account by the error estimation indicator, if and when necessary.
The new (geometric) wrinkling indicator in the $i$-principal direction is therefore defined as

$$e_i^w = \frac{1}{A} \int \frac{R_i^t - R_i^{t+\Delta t}}{R_i^t R_i^{t+\Delta t}} dA \quad i = 1,2 \qquad (2)$$

with $i$ representing the principal curvature (stress) direction and $R_i^t, R_t^{t+\Delta t}$ are the radii of curvatures in the *i*-direction at the beginning and at the end of a given deep drawing step, respectively.
The wrinkling indicator value $e^w$ is defined as the maximum of $e_i^w$, *i.e.*

$$e^w = max \left| e_i^w \right| \quad i = 1,2 \qquad (3)$$

An element is selected for refinement whenever $e_w$ is larger than the mean indicators value.

As for Hutchinson approach, the present indicator is local and is of a post-processing type, and is therefore determined at a very low computational cost.

## 5. NUMERICAL EXAMPLES

The performance of the wrinkling prediction procedure with adaptive mesh refinement described in this work is here demonstrated.
A hemispherical product is considered for wrinkling prediction analysis. The punch has a radius of 146.5mm and the die shoulder a radius of 30mm. The initial sheet thickness is 1mm and the product depth 100mm. Hollomon's hardening law is used with the

following set of parameters : $K = 542$, $n = 0.228$ and
$r = 2.2$. A deep drawing step size of 1mm has been chosen and DST finite elements exclusively used.

*5.1 Hemispherical product using the error estimator and the Hutchinson approach based wrinkling indicator*

In this numerical simulation a high blank holder force is used to avoid wrinkling under the blank holder as Hutchinson approach handles contact free wrinkling only.

The simulation is started with a relatively coarse mesh comprising 2050 elements and ended with an adapted mesh of 5400 elements as shown in Figure 1. The first refinement that takes place at step 30 is due to the thickness variation at the bottom of the product, the geometric error estimation in the region of the die shoulder and the wrinkling indicator that senses a potential for wrinkling in the wall of the product and, mostly in anticipation, refines the mesh.

In step 66, due to the mounting pressure under the blank holder in the die shoulder zone and because of the near flatness of the sheet the risk factor goes beyond one and consequently the refinement is intensified.

In the final step, this effect is increased which brings the final mesh to 5400 finite elements.

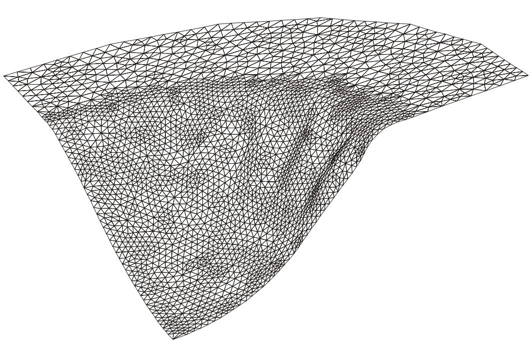

Figure 1. Final mesh (Contact free wrinkling).

*5.2 Hemispherical product using the error estimator and the geometric wrinkling indicator*

The initial mesh, again, comprises 2050 elements. The first refinement at step 32 is, as for the previous example, due to the geometric error estimation (around the die radius), to the geometric wrinkling indicator (in the flange) and to the thickness variation (at the bottom of the product). In step 64, the refinement is intensified around these regions.

It is noted that the drawing behaviour so far and consequently the mesh refinement is similar to the previous case whereby a high blank holder force is used.

In the final mesh comprising 8150 elements and shown in Figure 2, as expected, the refinement covers the whole area under the blank holder to properly describe the new buckles developing in that region of the sheet.

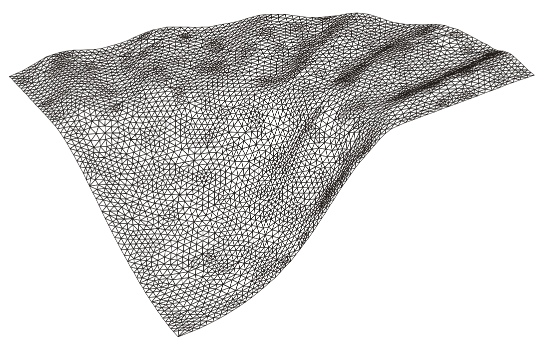

Figure 2. Final mesh (Wrinkling with contact).

## 6. CONCLUSIONS

It has been demonstrated that the use of adaptive mesh refinement in wrinkling prediction analysis is a necessary approach for reducing the computational cost and better describing the wrinkling phenomena. However, it is also found that this has to be linked with an error estimation routine to properly approximate the curvatures and the thickness as these play a major role in the

wrinkling process.
Hutchinson approach based wrinkling indicator that handles contact free wrinkling has been complemented with a new wrinkling indicator based on local curvature changes.

ACKNOWLEDGEMENTS

This research was carried out under project number ME97033 in the framework of the Strategic Research programme of the Netherlands Institute *for* Metals Research in the Netherlands (www.nimr.nl).

REFERENCES

1. A. Selman, T. Meinders, A.H. van den Boogaard and J. Huetink, *Wrinkling prediction with adaptive mesh refinement,* 3rd ESAFORM Conference on Material Forming, Stuttgart, 11-14 April, 2000.
2. A. Selman, T. Meinders, A.H. van den Boogaard and J. Huetink, *Numerical Analysis of Wrinkling in Sheet Metal Forming,* Submitted to Int. J. of Forming Processes, 2001.
3. A. Selman, T. Meinders, J. Huetink and A.H. van den Boogaard, *Comprehensive approach to wrinkling prediction analysis in thin sheet metal forming processes*, Submitted to Int. J. for Numerical Methods in Engineering, 2001.
4. P. Nordlund, *Adaptivity and wrinkle indication in sheet metal forming*, Compt. Meth. Appl. Mech. Engrg., 161, 127-143, 1998.
5. J. Bonet, *Error estimators and enrichment procedures for finite element analysis of thin sheet large deformation processes,* I.J.N.M.E., vol. 37, 1573 – 1591, 1994.
6. A. Selman, E. Hinton and N. Bicanic, *Adaptive mesh refinement for localised phenomena,* Comp. & Struct., vol. 63, 475 – 495, 1997.
7. J.W. Hutchinson and K.W. Neale, *Wrinkling of curved thin sheet metal,* Plastic Instability, J. Salencon (Ed.), Press Ponts et Chaussees, 71-78, 1985.
8. K.W. Neale, *Numerical analysis of sheet metal wrinkling,* Numiform ’89, Thompson et al (Eds.), 501-505, Balkema, Rotterdam, 1989.
9. J.W. Hutchinson, *Plastic buckling,* Adv. Appl. Mech., 14, 67-144, 1974.